STRENGTHENING OF ADOBE HOUSES FOR SEISMIC ACTIONS

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SUMMARY

In order to evaluate the efficiency of three strengthening methods for adobe houses, five 1:2.5 scale models were tested in a shaking table under the effect of the accelerograms of three major actual earthquakes. Mechanical properties of adobe masonry and structural behavior of adobe walls were also studied. The three strengthening methods evaluated were: a reinforced concrete bond beam at the top of the walls; a welded mesh nailed to both faces of the walls and covered by a mortar rendering; and steel rods tied to both faces of the walls in their upper part. The main objective of the reinforcement was to avoid separation of the walls in the corners and their subsequent overturning. Test results indicated that the seismic intensity that can be withstood without major damage is increased at least twice by any of the strengthening methods studied; the most efficient being the welded mesh reinforcement.

INTRODUCTION

In developing countries the main cause of loss of human lives and of economical damage following strong earthquakes is the collapse of small houses built of unreinforced masonry, mainly with adobes or stones bonded with mud mortar. One of the most dramatic examples is found in the Guatemala earthquake (1976), when due to the collapse of about 250,000 adobe houses more than 25,000 people died, this number representing about 98% of the total life toll.

Very little attention has been paid to the problem of increasing the safety of this type of construction and very few research programs have dealt with the subject. Perhaps one reason is the difficulty to transfer technological results to a medium where practically no technical personel is involved. Nevertheless, the magnitude of the problem demands both a number of efficient, practical and economical solutions and the actions of proper agencies in the field.

In the particular problem of adobe houses it is considered that, at least in Mexico, the cost involved in building new adobe houses with proper safety against earthquakes is at present higher than that of building brick or block masonry houses. Actually very few adobe houses are being built at present. The main problem is the lack of safety of many hundred thousands of unsafe adobe houses that exist in the seismic regions of the country. Considering this situation a research program has been undertaken at the Institute of Engineering of the National University of Mexico with the aim of evaluating different strengthening systems for single story low cost houses. The emphasis is placed on adobe houses but most results are valid for unreinforced masonry in general. Detailed reports on the research program can be found in the internal publication of the Institute (ref 1 and 2).

MODES OF FAILURE AND STRENGTHENING SYSTEMS

The weakness of adobe construction can only in part be ascribed to the poor

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quality of the material (unburnt earth brick) and to its degradation when subjected to the effect of the rain or to moisture changes. At least as important is the improper structural layout with low wall density, great height and great unsupported length of the walls; the large mass of the roof and the low restriction that the roof provides to the displacement of the walls normally to their plane contribute also to poor behavior. The aforementioned situation gives rise to the modes of failure illustrated in fig 1. The vibration of the longer walls normally to their plane induces bending moments that are maximum at their lateral ends and that produce vertical cracks that propagate downwards, in such a way that the upper part of the wall starts vibrating as a cantilever; overturning moments in the base of the cracked length become critical as the crack length increases and finally the wall falls generally outwards producing the collapse of the roof. When the laterally unsupported length of the walls is small, the in plane stiffness of the roof restricts the bending of the walls, or the shear strength of the wall is weakened by great window or door openings, the shear becomes critical and failure occurs by diagonal cracking (fig 1). Other failures are due to the collapse of the roof when its strength or its connections have been deteriorated by wheathering or to local problems as punching of the walls by a roof beam.

Being the flexural failure mode largely the most common, strengthening procedures have been focused mainly to achieve a proper connection between walls, to increase their strength and stiffness normally to their planes and to improve the connection between roof and wall and the in plane stiffness of the roof.

Perhaps the most widely proposed method of strengthening is the placement of a bond beam in the upper perimeter of the wall. The bonding element can be a wood truss as proposed in Chile, ref 3, or more commonly a concrete beam. With the last solution it is difficult to achieve proper bonding between adobe and concrete. Due to its large volume changes by shrinkage and moisture movements, adobe tends to separate from concrete and to loose the tightening effect of the beam. To overcome the problem a ribbed beam with a spur in the corner has been recently proposed and used in Mexico to strengthen adobe houses damaged by earth quakes (fig 2).

A much simpler procedure is the placement of horizontal steel ties, as in fig 3, which can be sligthly postensioned in order to precompress the wall. The procedure has been used to strengthen old stone masonry buildings damaged after Skopje and Friuli earthquakes (ref 4); its main advantage is that the roof does not need to be removed.

To achieve a more radical improvement of seismic behavior, vertical reinforcement is also needed. The concrete bond beam solution can be improved placing columns at the corners and at the ends of main openings, thus giving flexural strength in the plane of the wall and, more important, forming with the beam a concrete frame that provides confinement to the adobe walls, thus giving rise to a much more ductile behavior. The system is very efficient but rather complicated and expensive because the large wall thickness calls for very robust members; specials provisions must be adopted in order to ensure continuity between concrete columns and adobe walls. Systems with ties rods can be easily improved with vertical ties if there are stiff beams or footings at the foundation where the ties can be anchored; a system of this kind has been tested by Benedetti, ref 5.

A more comprehensive strengthening system has been proposed, ref 6, for damaged adobe houses in Mexico. It consists in covering both faces of the walls with a welded wire mesh on wich a thick mortar rendering is placed. A composite section is formed which has good flexural and shear strength; additional bars in the perimeter of the openings and in the upper end of the walls give additional strength. Essential to the good behavior of the system is the continuity of the mesh in the corners and the fastening of both meshes through steel ties that cross the wall and avoid local buckling and separation of the mesh (fig 4).

The three systems have been designed and used in the field but an evaluation of their effectiveness was lacking.

MECHANICAL PROPERTIES OF ADOBE MASONRY

To study the properties that have more influence in seismic behavior of buildings, samples of adobes made in several regions of Mexico were collected. Their compressive and tensile strength was determined and, as expected, a wide range was found. The mean strength was 10 kg/cm^2 for the compression test and 3 kg/cm^2 for the tension test with 30% coefficient of variation in both cases. The aforementioned strengths correspond to dry and underteriorated adobes. When adobes were moisted to a 10% water content compressive strength was reduced to 3 kg/cm^2 and tensile strength to less than 1 kg/cm^2.

With adobes fabricated in the lab to have the same average compressive and tensile strength as the samples, small walls were built to study the properties of adobe masonry with different mortars. Results tend to show that the properties of a wall with mud mortar are similar to those of the adobe and that the wall behaves essentially as a monolithic element. Average properties for the laborator fabricated adobe masonry walls were a shear strength by diagonal compression of 1.3 kg/cm^2, modulus of elasticity of 2,500 kg/cm^2 and shear modulus of 700 kg/cm^2. Modulus of elasticity and shear strength were increased when cement mortar was used in the joint, whereas strength and stiffness were reduced when lime mortars were used.

Two full scale walls with mud mortars were also tested under alternating lateral loads; with vertical ties at the ends of the wall the flexural failure was avoided and a shear failure was obtained for an average shear stress of 1.1 kg/cm^2. As shown in fig 5, after the first diagonal cracking the capacity of the wall to withstand alternating lateral load was reduced practically to zero.

DYNAMIC TESTS ON A SHAKING TABLE

The study of the dynamic behavior of adobe, or unreinforced mansory structures, does not lend itself to simple tests, mainly because of the difficulty of applying loads to the structures without producing local failures due to weakness of the material. The shaking table of the laboratory of structural dynamics of the Institute of Engineering was used to test models of adobe houses. The table, ref 7, of 2.4 x 4.5 m in plan, can receive models weighting up to 15 ton and can reproduce ground motions in the long direction of the table only. A prototype house was chosen with the dimensions shown in fig 6, which are common in the rural areas of Mexico and Central America, the main differences being in the weight of the roof. In hot humid or mild climate zones roof tiles on wood trusses are used (total roof weight of about 50 kg/m^2) whereas in more severe climates earth roofs over closely spaced wood beams are common (roof weights up to 500 kg/m^2). Table size limitations required that only a part of the structure be tested or that reduced scale models be used.

The second solution was favored and a geometric scale of 1:2.5 was chosen. Dimensional requirements for dynamic tests can be complied with if the weight of the materials is multiplied by the geometric scale factor or if their modulus and strength against any possible mode of failure is divided by the same factor. Any of the alternatives is difficult to accomplish for the type of structure considered. If none of these properties is modified, the dynamic behavior of the prototype can be reproduced by properly modifying the time and acceleration scales of the input, but the static stresses in the model due to the own weight of the structure are equal to those in the prototype divided by the scale factor. It was considered important to reproduce exactly the material and the joints, so adobe bricks were built in the lab with the same technique and materials as in the field. Different types of earth and straw contents were tried until the mean compressive and tensile strengths of the adobe sampled in the field were obtained. To obtain static stresses closer to those required, additional weights were distributed in the walls so as to increase the density of the material by a factor equal to the square root of the scale factor ($\sqrt{2.5}$). Thus, stresses in the model due to its own weight were 63% of those required. It was considered that this difference would not affect significantly the dominant mode of failure due to horizontal bending of the walls and that results would be slightly conservative regarding overturnuning and shear failures.

The records of three important earthquakes with high spectral amplitudes for low periods were selected, considering that this type of movement would be more critical for the adobe houses. The El Centro (1940) Managua (1972) and Oaxaca (1973) records were selected and had to be corrected according with dimensional analysis requirements; low frequency movements had also to be filtered in order to limit the maximum ground displacement to that allowed by the actuator of the shaking table (2.5 cm). The spectra of the original records and those calculated from the movement of the shaking table are compared in fig 5 for the three earthquakes. It can be seen that, except for very low periods in the El Centro and Oaxaca earthquakes, spectra of the recorded motions fitted acceptably well those of the original records.

The models reproduced the typical house shown in fig 6; scaled down roof trusses and tiles were placed only in the first test; in other tests equivalent masses were placed on steel channels simply supported on the walls, giving rise to a situation slightly less favorable than that in reality, as the beams imposed practically no restriction to the movement of the walls. Models were placed on the table in such a way that the movement of the latter was normal to the longest side of the house thus favoring bending failure of longest walls.

Five models were tested; three of them were built independently, two without reinforcement and one with a concrete bond beam; the two remaining models were obtained by strengthening the two unreinforced models after they were tested very near to total collapse.

In the first three models different table movements were applied and the type of roof was also changed. After recognizing that with the Oaxaca record more severe damages could be obtained, in the remaining tests only this record was applied increasing its intensity until reaching the collapse or the maximum capacity of the actuator. In order to obtain a measure of the amount of damage suffered by the models, after each level of seismic motion a free vibration test was performed measuring the period and damping of the movement in the four walls.

Six accelerometers were placed in different positions as shown in fig 6.

RESULTS OF SHAKING TABLE TESTS

A first objective of tests was to check the validity of using finite element dynamic linear elastic analyses for adobe houses. The fundamental period and the modal shape obtained in the models before being submitted to high amplitues of ground motions were very similar to the calculated one. These results demostrate that finite element analyses can be used to study the effect of a wide range of variables in the dynamic behavior, wherefrom simple rules for the design can be derived, as made in ref 2.

The amount of damage suffered by the models can be related with their loss of stiffness and consequently their increase in fundamental period, and with the increase in damping due to friction in the cracks. The variation of period and damping with the intensity of motion, shown in fig 8, allows to detect a drastic change that corresponds to major damage. To establish a basis for the comparison of the results of the different models it was considered as major damage that corresponding to an increase of 50% in period.

The behavior of the five models tested can be summarized as follows. Model 1, unreinforced, supported without major damage 50% of the actual intensity of the El Centro record. At about that intensity vertical cracks in the corners separated the walls; the length of the cracks increased in the following tests and for 90% of the intensity, the model was severily distressed; the total collapse did not occur, although the walls could be overturned with a slight push of one hand. It is believed that the elimination of low frequency motions from the original record canceled the large displacement that the structure would have suffered under the actual record; this prevented collapse.

Model 2, reinforced with a concrete bond beam, withstood without apparent damage 90% of the El Centro record and showed important distress caused by major vertical cracking below the concrete spur in the corners for 3.6 times the intensity of the Oaxaca earthquake. After testing, model 1 was reinforced by filling major cracks with mud and by placing the wire mesh and cement rendering in both faces as previously described. The house was tested again and identified as model 3. Starting at intensities approximately equal to the actual record, the mortar began to separate from the adobe, to crack and to fall down. Nevertheless the wire mesh nailed to the wall maintained the continuity of the structure, wich could withstood without collapse the maximum intensity that could be applied by the actuator, 4.6 times the Oaxaca record. Models 2 and 3 were subjected withouth major damage to the full intensity of El Centro and Managua records.

Model 4 was also unreinforced and was subjected to the Oaxaca record in order to establish a basis of comparison for the strength of the different models and to obtain a damaged structure to be strengthened by a different method. The mode of failure was similar to that of model 1 and it was considered failed at 1.35 times the intensity of the actual record. When reinforced with horizontal ties it withstood twice the intensity supported by the unreinforced model. Failure was due to severe vertical cracks in the corners and to horizontal flexural cracks in the long walls.

It is considered that the intensities withstood by the models cannot be quantitatively extrapolated to prototypes due to limitations of the tests; only horizontal motion in one direction was applied, low frequency motion was eliminated and vertical stresses were not respected. Nevertheless the efficiency of the differents strengthening methods can be compared. It is concluded that the three methods enhance significantly the strength of the structure and that the efficiency of the concrete beam and steel ties methods is limited by the lack of vertical reinforcement, the beneficial effect of which is evident in the model reinforced with wire mesh.

CONCLUSIONS

The problem of strengthening existing adobe houses has to be faced with solutions that give rise to proper safety against earthquakes and that can be executed with simple techniques and at low cost. Use of wire mesh reinforcement is considered a very efficient method, as it not only enhances the seismic safety but also protects adobe from weathering. Nevertheless it requires a higher amount of steel than the other methods and for the proper placement of the mesh the roof needs to be removed at least by parts. From the point of view of cost and easiness of construction the reinforcement with steel ties is the most convenient one; to achieve a higher safety, additional vertical ties are needed in the corners and at the ends of the openings. Anchoring of vertical ties at a foundation beam or footing is needed. The efficiency of the concrete bond beam can also be singnificantly increased if it is tied to the foundation by vertical reinforcement.

The three strengthening methods cover only the more essential aspects of the reinforcement. Several additional details have to be considered to obtain proper safety: in plane stiffening of the roof to form a diaphragm; tying together of roof and walls, and placing of reinforcement around openings. Very good results can be obtained also by modifiying the house layout, as well as by reducing the weight of roof and the height and unsupported length of the walls.

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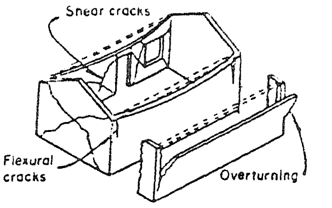

Fig. 1 Modes of failure of unreinforced masonry houses

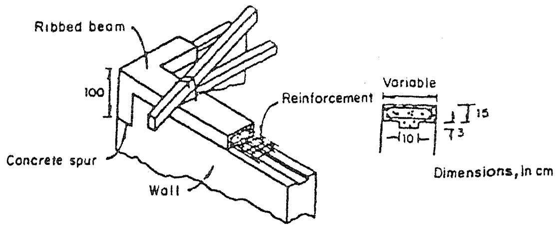

Fig 2. Strengthening with a concrete bond beam

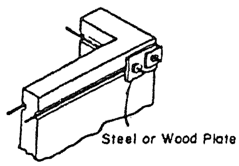

Fig 3. Strengthening with steel ties

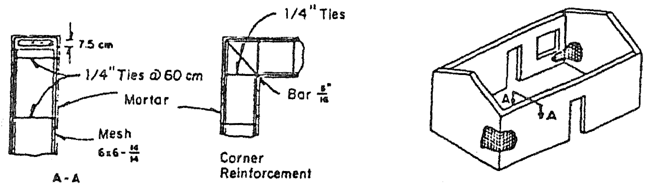

Fig 4. Strengthening with wire mesh and mortar

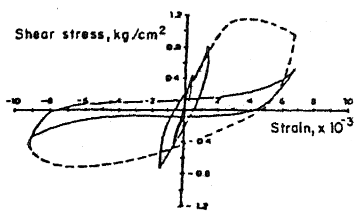

Fig 5. Hysteresis loop under lateral loads of an adobe wall

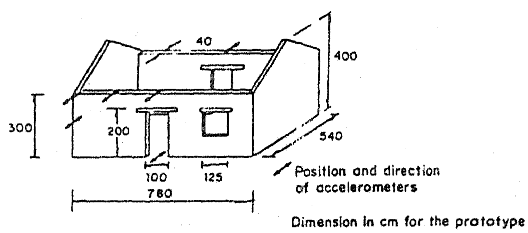

Fig 6. Typical adobe house tested in the skaking table

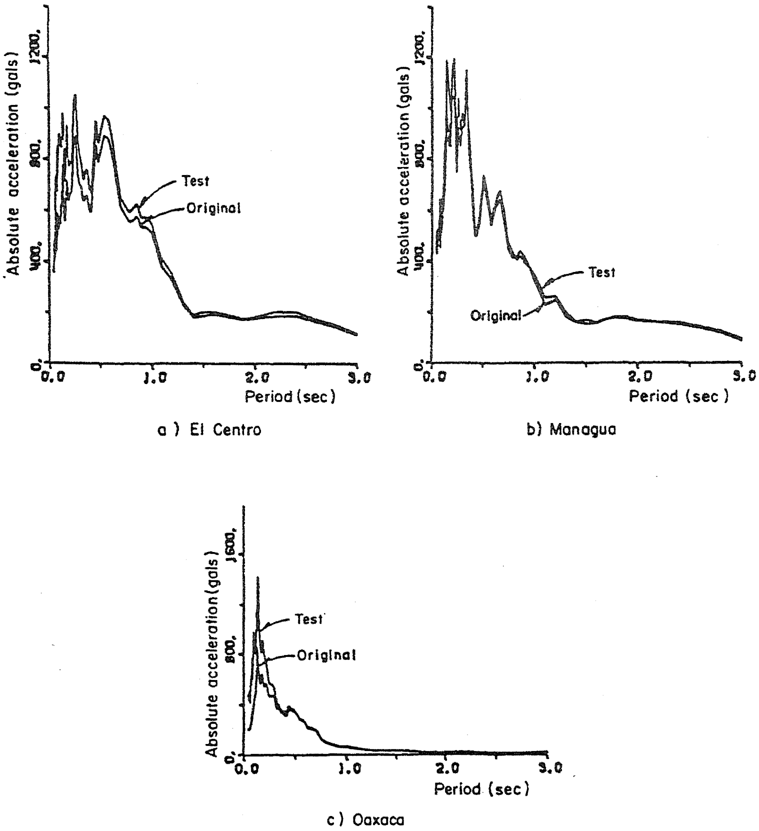

Fig 7. Spectra of the seismic motions used in the tests

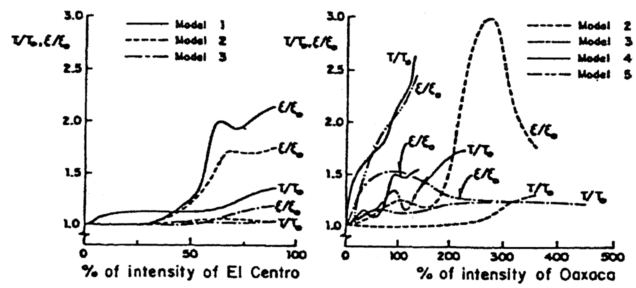

Fig 8. Variation of period and damping after tests with different levels of seismic excitation